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ORDOVICIAN MAGMATISM IN THE EXTERNAL FRENCH ALPS: WITNESS OF A PERI-GONDWANAN ACTIVE CONTINENTAL MARGIN

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INTRODUCTION

The pre-Mesozoic basement areas of the external Alpine domain (e.g. Aiguilles-Rouges Mont-Blanc, Aar Gotthard crystalline massifs) are underlain by former early Palaeozoic sedimentary and magmatic rock units, which underwent a high-grade metamorphic overprint during the Carboniferous Variscan orogenic events. On the other hand, they were fairly well preserved from the Tertiary Alpine metamorphism, which reached only lower greenschist facies conditions (von Raumer et al., 2009, with references) and moderate deformation. Pre-Variscan lithologies are particularly well documented in the Aiguilles Rouges massif, west of Chamonix (France). Here we present new age determinations on several magmatic bodies of this massif. Together with pre-existing geochronological and geochemical data, they document a major magmatic event of Ordovician age which can be related to an active margin geodynamic environment.

GEOLOGICAL FRAMEWORK

The Aiguilles Rouges massif (ARM) is one of the so-called external crystalline massifs of the Alpine belt and corresponds to a huge Alpine basement antiform structure of 20 by 45 km surrounded by Mesozoic sedimentary cover units (geological maps and lithologic descriptions in von Raumer and Bussy, 2004). The lithologies include various metasedimentary rocks like metagreywackes, banded paragneisses, quartzites, micaschists, as well as orthogneisses and metabasites like garnet-amphibolite and eclogite boudins. Pre-Mesozoic metamorphic assemblages record at least two distinct P-T events. In the Lake Cornu area, mafic eclogites preserve high-pressure garnet-omphacite metamorphic assemblages, recording P-T conditions of > 1.1 to 1.4 GPa and 700°C, respectively (Liégeois and Duchesne, 1981). The age of this high-P event is unknown, but predates the Variscan high-T event described below. In the Lake Emosson area, metagrawackes have partially melted yielding migmatites with up to 25 vol.-% leucosome. According to Genier et al. (2008), anatexis was triggered by water fluxing of metagreywackes in a transcurrent shear-zone at 0.3-0.4 GPa and 640-670°C. Monazite from a leucosome vein yielded a U-Pb date of 321 Ma (Bussy et al., 2000), interpreted as the age of leucosome crystallization. More recently, Schulz and von Raumer (2011) obtained electron microprobe dates of ca. 440 Ma on monazite grains included in garnet in micaschists. These dates document a pre-Variscan high-T event distinct from that of the Emosson migmatites.

ORDOVICIAN MAGMATISM

Apart from late Carboniferous continental detrital deposits (Salvan-Dorénaz syncline, Capuzzo and Bussy 2000) and granite intrusions (Vallorcine granite, Fully granodiorite, Bussy et al. 2000), all other lithologies of the ARM predate the 320 Ma-old Variscan high-T metamorphic event, but no relative chronology can be established among them, as no primary contacts are preserved.

Mafic magmatism is of little volumetric importance. It is mainly documented as swarms of metre-long garnet-amphibolite boudins within micaschists; they have a geochemical signature of continental tholeiites (von Raumer et al., 1990) and their age is unknown. More continuous outcrops are found in the Lake Cornu area, with layers up to several tens of metres long. They consist of mafic eclogites variously retrogressed into garnet-amphibolites. The eclogites are either massive and isotropic or banded with alternating cm-thick dark layers of garnet-amphibole-quartz-plagioclase and light layers of coronitic garnet-clinopyroxene-plagioclase. This layering has been interpreted by Liégeois and Duchesne (1981) as evidence for a volcanic-sedimentary origin. Alternatively, Péronnet (2009) has shown that the only difference between light and dark layers is the relative proportion of amphibole and diopside originating in the retrogression of the original eclogitic assemblage. Thus the limited amount of available water at time of retrogression might have controlled the development of the banding in originally homogeneous eclogites. Nevertheless, some light layers of the banded eclogites are relatively enriched in Al and Sr and display strong positive Eu anomalies in chondrite-normalized REE patterns. This is indicative of plagioclase accumulation and might record in situ mineral fractionation during basalt crystallization. Liégeois and Duchesne (1981) interpret the Lake Cornu eclogites as various terms of the low pressure differentiation of a continental tholeiite and suggest emplacement in a thinned continental crust environment. This is in agreement with the data of Paquette et al. (1989), who concluded that the massive eclogites have N-MORB REE signatures and positive initial epsilon Nd values between 5.9 to 6.8. Paquette et al. (1989) also performed isotope-dilution U-Pb dating on large zircon fractions extracted from a Lake Cornu eclogite. They obtained an upper intercept date of 453 +3/-2 Ma interpreted as the magmatic age of the mafic protolith of the eclogite.

Interestingly, a few ultramafic boudins of serpentinite up to 100 m long are wrapped in paragneisses in the Lake Cornu area. Their chemistry points to former lherzolites and pyroxenites (Pfeifer and von Raumer, 1996; von Raumer and Bussy, 2004).

Granitic magmatism is expressed as large volumes of orthogneisses in the ARM. The most common facies is a porphyritic biotite±muscovite augengneiss with K-feldspar megacrysts up to 5-10 cm long (e.g. Emosson, Bérard, Lac Noir). Other lithologies include amphibole-biotite orthogneisses (Bérard) and some leucogneisses. The augengneisses are peraluminous (A/CNK=1.4) granodiorites to monzogranites. Their zircons display morphologies typical of S-type granites (Pupin, 1980). The amphibole-biotite orthogneisses are metaluminous granodiorites to tonalites typical of I-type calc-alkaline series, as confirmed by zircon morphology and whole-rock geochemistry (von Raumer and Bussy, 2004).

GEOCHRONOLOGY

Five rock samples have been dated by U-Pb zircon geochronology. In situ isotopic measurements have been performed by LA-ICPMS using an Element XR sector-field spectrometer interfaced to an UP-193 excimer ablation system. The instrument was calibrated using a GJ-1 zircon as external standard. Accuracy was monitored by analysing the Harward 91500 standard as an unknown. The systematic error of the 91500 standard measurements is <1% for any of the sequences. The U-Pb ages reported here correspond to the weighted mean of individual $^{206}Pb/^{238}U$ age determinations.

Banded eclogite sample ViP44 (Swiss grid coordinates 89.758/554.105) yielded rounded zircons about 50 to 100 microns in diameter. Cathodoluminescence (CL) imaging (Fig. 1a,b) reveals the common association of an oscillatory zoned rounded core and an unzoned rim of homogeneous colour, which can be either darker (higher in U) or lighter (lower in U) than the core. The core is interpreted as magmatic, whereas the homogeneous rim is considered metamorphic. 43 out of 55 concordant measurements on zircon cores were statistically selected as a coherent group by the "zircon age extractor" subroutine of Isoplot (Ludwig, 2009); they yield a mean $^{206}Pb/^{238}U$ age of 463 +3/-2 Ma (Fig. 2a) interpreted as the magmatic age of the mafic protolith. Measurements in the rims yielded inconsistent dates older than the magmatic cores (Fig. 1a).

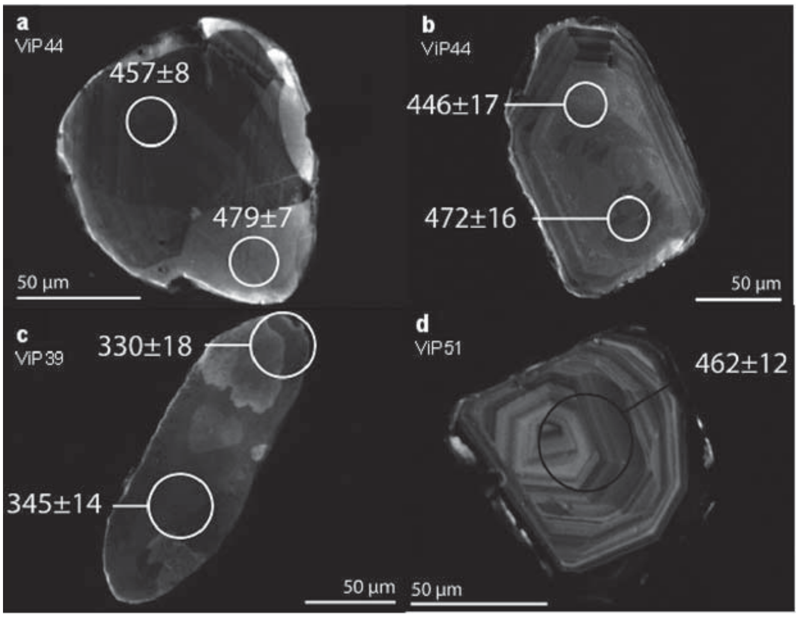

Figure 1. Cathodoluminescence images of zircon crystals with position of the ablation craters and corresponding individual $^{206}Pb/^{238}U$ ages (± 2 sigma).

Eclogitic amphibolite sample ViP39 (Swiss grid coordinates 89.757/554.083) yielded rounded zircons very similar to those of the banded eclogite. 54 out of 75 concordant measurements on zircon cores were statistically selected as a coherent group (Ludwig, 2009); they yield a mean $^{206}Pb/^{238}U$ age of 458 ± 5 Ma (Fig. 2b), identical within errors to the age of the massive eclogite ViP44. Among the remaining

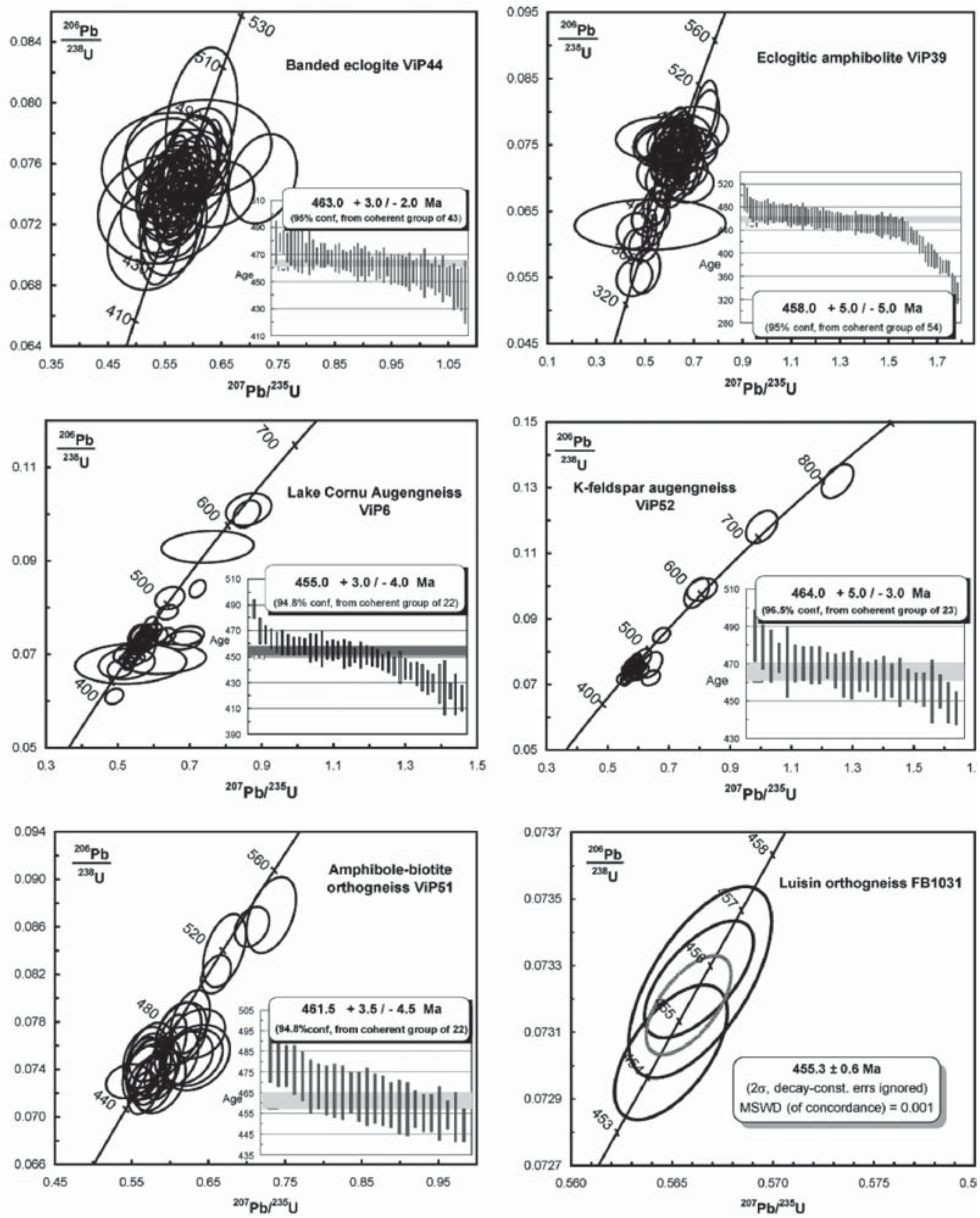

Figure 2. U-Pb concordia plots for the dated lithologies; reported ages are mean $^{206}Pb/^{238}U$ ages calculated with the "zircon age extractor" subroutine of Isoplot (Ludwig, 2009), see inserts. Sample FB1031 has been dated by the isotope dilution (IDTIMS) technique and the reported age is the Concordia age (Ludwig, 2009). All errors are given at the two-sigma level.

measurements, two are older and discordant ($^{206}Pb/^{238}U$ dates of 492 and 496 Ma, respectively); they probably contain an inherited component. 16 other data points spread down to a concordant point at 345 Ma ($^{206}Pb/^{238}U$ age = 345 ± 14 and $^{207}Pb/^{235}U$ age = 346 ± 43 Ma) (Fig. 1c and 2b); they are interpreted as mixed ages between a magmatic component at 458 Ma and a metamorphic event close to 345 Ma, which might correspond to the high-pressure metamorphic event.

Lake Cornu augengneiss ViP6 (Swiss coordinates 90.423/554895) is representative of the widely distributed biotite-muscovite peraluminous K-feldspar orthogneisses. It yielded relatively big zircons with a well-developed {211} pyramid typical of Al-rich melts (Pupin, 1980). The internal CL structure shows inherited cores wrapped by large oscillatory growth zones of magmatic origin. Metamorphic overgrowths are usually lacking. A statistically consistent group of 22 out of 45 analyses yield a mean $^{206}Pb/^{238}U$ date of 455 +3/-4 Ma, interpreted as the crystallization age of the porphyric granite (Fig. 2c). Older concordant dates range from 470 to 1035 Ma and are interpreted either as mixed ages or as related to inherited cores. Younger dates spread down to 384 Ma and are interpreted as data points disturbed by metamorphic remobilization.

The Val Bérard ViP52 K-feldspar augengneiss is similar to sample ViP6 and yielded zircons of the same kind, except that the {211} pyramid is less developed and that no inherited cores have been observed on CL images. A statistically consistent set of 23 out of 32 analyses yield a mean $^{206}Pb/^{238}U$ date of 464 +5/-3 Ma, interpreted as the magmatic age of the porphyric granite (Fig. 2d). It is slightly older than the Lake Cornu augengneiss.

The Val Bérard ViP51 amphibole-biotite metaluminous orthogneiss (French grid coordinates 950.125/121.855) yielded zircons up to 150 microns long with some inherited cores and a generally well-developed oscillatory zoning (Fig. 1d). Many crystals are metamictic and were partly dissolved during the leaching procedure. 22 out of 32 measurements define a statistically coherent group which yields a mean $^{206}Pb/^{238}U$ date of 461.5 +3.5/-4.5 Ma, interpreted as the magmatic age of the granodiorite (Fig. 2e). Some older concordant dates ranging between 500 and 735 Ma point to inherited cores or crystals.

In addition, a sample from the calc-alkaline metaluminous orthogneiss of Mt Luisin north of Lake Emosson (FB1031) has been dated in the nineties at the Royal Ontario Museum by U-Pb zircon geochronology using the isotope dilution technique (ID-TIMS). The applied analytical procedure is described in Bussy and Cadoppi (1996). Three small zircon fractions yielded a concordia age of 455.3 ± 0.6 Ma (MSWD = 0.001) (Fig. 2f).

DISCUSSION

All pre-Variscan magmatic rocks of the ARM emplaced in a relatively short time span between 455 and 465 Ma. The same is true for a large augengneiss body from the neighbouring Mont Blanc massif dated at 453 ± 3 Ma (Bussy and Von Raumer, 1994). The amphibole-biotite granodiorite (ViP51) and the Mt Luisin granodiorite (FB1031) are I-type metaluminous granitoids with mafic microgranular enclaves typical of calc-alkaline magmatic series. On the other hand, the voluminous K-feldspar augengneiss found both in the Aiguilles Rouges (Bérard (ViP52), Lac Noir (ViP6), Mont-Blanc (Morard, 1998)) are relatively peraluminous as confirmed by their zircon morphology, but they do not display the characteristic features of classical S-type granites like restitic enclaves and schlieren or large amounts of primary muscovite. We interpret the corundum-normative character of these intrusions as acquired through high-pressure (>0.8 GPa) fractional crystallization processes of standard metaluminous calc-alkaline melts in lower crustal levels (see e.g. Alonzo-Perez et

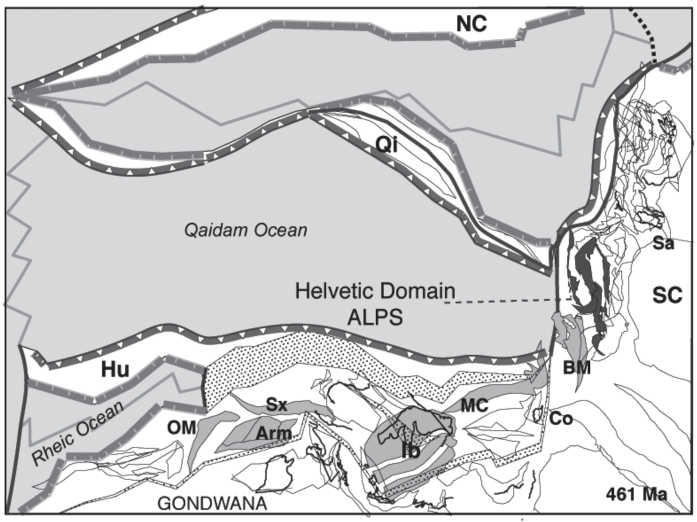

Figure 3. Ordovician (461 Ma) plate tectonic reconstruction (after Stampfli et al., this volume: Fig. 1D), showing the future Alpine Geodynamic units (dark grey), in the frame of the Ordovician basement areas, at the eastern limits of the Qaidam Ocean, spanning between the Qilian basement in the north and the Hunic terranes (Hu), still located at the Gondwana margin. The future eastern branch of the Rheic Ocean is not yet opened. Specific basement areas in light grey: Arm, Armorican terrane assemblage; BM, Bohemian massif and Barrandian areas; Co, Corsica; Ib, Iberian terrane assemblage; MC, Massif Central; NC, North China; Qi, Qidam; Sa, Sardinia; SC, South China; Sx, Saxothuringian domain; OM, Ossa Morena; dotted spaces, sedimentary troughs with detrital sediments (e.g. Armorican quartzite).

al. 2009). The close spatial association of the calc-alkaline granite plutons with minor volumes of mafic rocks of tholeiitic affinity is probably not original, but might result from Variscan tectonics. Indeed, the distribution of the (retro)eclogite mafic boudins in paragneisses is reminiscent of the tectonic accretion channel of a suture zone (Engi et al., 2001). If true, the basaltic sills(?) might have emplaced away from the granite plutons, like in an extensional basin in a back-arc geodynamic environment.

Ordovician magmatism is recorded all over the Alpine basement units. It extends from 470 to 440 Ma in the external crystalline massifs (see review in von Raumer et al., 2002) and from ca. 480 to 450 Ma in the Penninic and Austroalpine domains (e.g. Guillot et al., 2002; Schulz et al., 2008; Liati et al., 2009). The general picture is the following (see review in Schaltegger and Gebauer, 1999): an early mafic activity locally coeval with orthogneisses is documented by gabbros in various units (Silvretta nappe, Gotthard, Tavetsch and Aar massifs) between 471 and 467 Ma. Many large granite plutons emplaced between 470 and 450 Ma, whereas a regional high-T metamorphic event with partial melting is recorded in the Aar and Gotthard massifs at ca. 445-450 Ma and in the ARM at ca. 440 Ma by monazite in garnet micaschists (Schulz and von Raumer, 2011).

The Ordovician magmatism in the future Alpine realm is quite distinct from that developed during the subsequent Variscan orogeny. The latter is characterized by 340 Ma-old Mg-K-rich monzogranites emplaced along lithospheric-scale transcurrent faults tapping an enriched subcontinental mantle source (Debon and Lemmet, 1999), and by abundant migmatites and cordierite-bearing peraluminous granites like in the Velay dome (French Massif Central), which evidence a very high thermal flux unknown in Ordovician lithologies. The Ordovician context is more reminiscent of an active continental margin of western north American type.

Current geodynamic reconstructions generally agree on the existence of a Cambrian active continental margin all along northern Gondwana, consequence of the southward subduction of the Iapetus ocean to the west and the Prototethys ocean to the east (e.g. von Raumer and Stampfli, 2008; Schulz et al. 2008; Guillot and Ménot, 2009). On the other hand, models significantly diverge in detail for the post-Cambrian evolution of this margin (compare e.g. Stampfli et al., this volume; Guillot and Ménot, 2009). The widespread Ordovician magmatism in the future Alpine realm on the one hand and the new geochronological data in the ARM on the other hand bring two important constraints to geodynamic models. First, the future Alpine terranes must be located relatively close (up to a few hundreds km) to the oceanic trench of the north Gondwanan active margin from 480 to 450 Ma (see e.g. Stampfli et al. 2011), as large volumes of calc-alkaline granites emplaced during that time. Second, the contemporaneous mafic rocks of tholeiitic affinity most probably emplaced in a different setting, possibly in a back-arc extensional basin locally floored by exhumed subcontinental mantle, now preserved as mega serpentinite boudins in the ARM. The mafic rocks were subsequently subducted during the Variscan orogeny (possibly at ca. 345 Ma, sample ViP39) and involved in a tectonic accretion channel which brought them back to mid-crustal levels as eclogitic boudins.

The thermal event recorded by the 450 Ma-old migmatites in the Aar massif (Schaltegger and Gebauer, 1999) and 440 Ma-old monazites in high-grade micaschists from the ARM (Schulz and von Raumer, 2011) might either be linked to the voluminous magmatic activity in these terranes at that time or to a high heat flux related to crustal extension, possibly the back-arc extension which will ultimately open the Paleotethys ocean (see reconstructions by Stampfli et al., this volume).

REFERENCES

Alonso-Pérez, R., Müntener, O. and Ulmer, P. 2009. Igneous garnet and amphibole fractionation in the roots of island arcs: experimental constraints on H2O undersaturated andesitic liquids. *Contributions to Mineralogy and Petrology*, 157, 541–558.

Bussy, F. and Cadoppi, P. 1996. U-Pb zircon dating of granitoids from the Dora-Maira massif (western Italian Alps). *Schweizerische Mineralogische und Petrographische Mitteilungen,* 76, 217-233.

Bussy, F. and von Raumer, J. 1994. U-Pb geochronology of Palaeozoic magmatic events in the Mont-Blanc Crystalline Massif, Western Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 74, 514-515.

Bussy, F., Hernández, J. and Von Raumer, J. 2000. Bimodal magmatism as a consequence of the post-collisional readjustment of the thickened variscan continental lithosphere (Aiguilles Rouges/Mont-Blanc massifs, western Alps). *Transactions Royal Society of Edinburgh*, 91, 221-233.

Capuzzo, N. and Bussy, F. 2000. High-precision dating and origin of synsedimentary volcanism in the Late Carboniferous Salvan-Dorénaz basin (Aiguilles-Rouges Massif, Western Alps). *Schweizerische Mineralogische und Petrographische Mitteilungen*, 80, 147-168.

Debon, F. and Lemmet, M. 1999. Evolution of Mg-K ratios in the Late Variscan Plutonic Rocks from the External Crystalline Massifs of the Alps (France, Italy, Switzerland). *Journal of Petrology,* 40, 1151–1185.

Engi, M., Berger, A. and Roselle, G.T. 2001. Role of the tectonic accretion channel in collisional orogeny. *Geology,* 29, 1143–1146.

Genier, F., Bussy, F., Epard, J.L. and Baumgartner, L. 2008. Water-assisted migmatization of metagreywackes in a Variscan shear-zone (Aiguilles Rouges massif, western Alps). *Lithos*, 102, 575-597.

Guillot, F., Schaltegger, U., Bertrand, J.M., Deloule, E. and Baudin, T. 2002. Zircon U-Pb geochronology of Ordovician magmatism in the polycyclic Ruitor massif (Internal W Alps). *International Journal of Earth Sciences,* 91, 964-978.

Guillot, S. and Ménot, R.P. 2009. Paleozoic evolution of the External Crystalline Massifs of the Western Alps. *Comptes Rendues Geoscience,* 341, 253-265.

Liati. A, Gebauer, D. and Fanning C.M. 2009. Geochronological evolution of HP metamorphic rocks of the Adula nappe, Central Alps, in pre-Alpine and Alpine subduction cycles. *Journal Geological Society London*, 166 (4), 797-810.

Liégeois, J.P. and Duchesne, J.C. 1981. The Lac Cornu retrograded eclogites (Aiguilles-Rouges Massif, Western Alps, France): evidence of crustal origin and metasomatic alteration. *Lithos*, 14, 35-48.

Ludwig, K. 2009. *Isoplot 3.6, a geochronological toolkit for Microsoft Excel*. Berkeley Geochronology Center, special publication 4, 77pp.

Morard, A. 1998. *Pétrographie et cartographie du socle du massif du Mont-Blanc dans le secteur de la Montagne de Lognan (Argentière, France).* Diploma Thesis, Université de Lausanne, 138 pp. (Unpublished)

Paquette, J.L., Ménot, R.P. and Peucat, J.J. 1989. REE, SM-Nd and U-Pb zircon study of eclogites from the Alpine External Massifs (Western Alps): evidence for crustal contamination. *Earth and Planetary Science Letters,* 96, 181-189.

Péronnet, V. 2009. *Pétrologie, géochimie et géochronologie du socle pré-mésozoïque de la région du Lac Cornu, Aiguilles-Rouges (France).* Master thesis, University of Lausanne, 136 pp. (Unpublished)

Pfeifer H.R. and von Raumer, J. 1996. Lherzolitic and proxenitic ultramafics from the Lac Cornu area (Aiguilles-Rouges Massif, France). *Schweizerische Mineralogische und Petrographische Mitteilungen*, 76 (1), 119.

Pupin, J.P. 1980. Zircon and granite petrology. *Contributions to Mineralogy and Petrology,* 73, 207-220.

von Raumer, J.F. and Bussy, F. 2004. Mont Blanc and Aiguilles Rouges, Geology of their polymetamorphic basement (External Massifs, Western Alps, France-Switzerland). *Mémoires de Géologie (Lausanne)*, 42, 204 pp.

von Raumer, J. and Stampfli, G.M. 2008. The birth of the Rheic Ocean – Early Palaeozoic subsidence patterns and tectonic plate scenarios. *Tectonophysics,* 461, 9-20.

von Raumer, J., Bussy, F. and Stampfli, G.M. 2009. The Variscan evolution in the Alps – and place in their Variscan framework. *Comptes Rendues Geosciences*, 341, 239-252.

von Raumer J.F, Galetti G, Pfeifer H.R. and Oberhänsli, R. 1990. Amphibolites from Lake Emosson/Aiguilles-Rouges, Switzerland: Tholeiitic basalts of a Paleozoic continental rift zone. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 70, 419-435.

von Raumer, J.F., Stampfli, G. M., Borel, G. and Bussy, F. 2002. The organization of pre-Variscan basement areas at the north-Gondwanan margin. *International Journal Earth Sciences,* 91, 35-52.

Schaltegger, U. and Gebauer, D. 1999. Pre-Alpine geochronology of the Central, Western and Southern Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 79, 79-87.

Schulz, B. and von Raumer, J. 2011. Discovery of Ordovician–Silurian metamorphic monazite in garnet metapelites of the Alpine External Aiguilles Rouges Massif. *Swiss Journal of Geosciences.* doi 10.1007/s00015-010-0048-7.

Schulz, B., Steenken, A. and Siegesmund, S. 2008. Geodynamic evolution of an Alpine terrane - the Austroalpine basement to the south of the Tauern Window as a part of the Adriatic Plate (eastern Alps). In Siegesmund, S., Fügenschuh, B. and Froitzheim, N. (eds.), *Tectonic Aspects of the Alpine-Dinaride-Carpathian System. Geological Society of London, Special Publication,* 298, 5-44.